

CONSTRAINED-ENVELOPE DIGITAL-COMMUNICATIONS TRANSMISSION SYSTEM AND METHOD THEREFOR

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to the field of digital communications. More specifically, the present invention relates to the field of constrained-envelope digital transmitter circuits.

BACKGROUND OF THE INVENTION

A wireless digital communications system should ideally refrain from using any portion of the frequency spectrum beyond that actually required for communications. Such a maximally efficient use of the frequency spectrum would allow the greatest number of communications channels per given spectrum. In the real-world, however, some spectral regrowth (i.e., increase in spectral bandwidth) is inevitable due to imperfect signal amplification.

In wireless communication systems various methodologies have been used to minimize spectral regrowth. Some conventional methodologies utilize complex digital signal processing algorithms to alter a digitally modulated transmission signal in some manner conducive to minimal spectral regrowth. Such complex algorithmic methodologies are well suited to low-throughput applications, i.e., those less than 0.5 Mbps (megabits per second), such as transmission of vocoder or other audio data. This is because the low throughput rate allows sufficient time between symbols for the processor to perform extensive and often repetitive calculations to effect the required signal modification. Unfortunately, high-throughput applications, i.e., those greater than 0.5 Mbps, such as the transmission of high-speed video data, cannot use complex processing algorithms because the processing power required to process the higher data rate is impractical.

A digital signal processing methodology may be used with the transmission of burst signals. With burst transmissions, the interstitial time between bursts may be used to perform the necessary complex computations based upon an entire burst. This methodology is not practical when continuous (as opposed to burst) transmission is used.

A conventional form of post-modulation pulse shaping to minimize spectral bandwidth utilizes some form of Nyquist-type filtration, such as Nyquist, root-Nyquist, raised cosine-rolloff etc. Nyquist-type filters are desirable as they provide a nearly ideal spectrally constrained waveform and negligible inter-symbol interference. This is achieved by spreading the datum for a single constellation phase point over many unit baud intervals in such a manner that the energy from any given phase-point datum does not interfere with the energy from preceding and following phase-point data at the appropriate baud-interval sampling instants.

The use of Nyquist-type filtration in a transmission circuit produces a filtered signal stream containing a pulse waveform with a spectrally constrained waveform. The degree to which a Nyquist-type pulse waveform is constrained in bandwidth is a function of the excess bandwidth factor, α . The smaller the value of α , the more the pulse waveform is constrained in spectral regrowth. It is therefore desirable to have the value of α as small as possible. However, as the value of α is decreased, the ratio of the spectrally constrained waveform magnitude to the spectrally unconstrained waveform magnitude is increased. The spectrally unconstrained waveform is the waveform that would result if no action were taken to reduce spectral regrowth. Typical

designs use a values of 0.15 to 0.5. For an exemplary a value of 0.2, the magnitude of the spectrally constrained waveform is approximately 1.8 times that of the unconstrained waveform. This means that, for a normalized spectrally unconstrained waveform magnitude power of 1.0, the transmitter output amplifier must actually be able to provide an output power of 3.24 (1.8^2) to faithfully transmit the spectrally constrained waveform. This poses several problems.

When the transmitter output amplifier is biased so that the maximum spectrally unconstrained waveform (1.0 normalized) is at or near the top of the amplifier's linear region, all "overpower" will be clipped as the amplifier saturates. Such clipping causes a marked increase in spectral regrowth, obviating the use of Nyquist-type filtration.

When the transmitter output amplifier is biased so that the maximum spectrally constrained waveform (1.8 normalized) is at or near the top of the amplifier's linear region, the spectrally unconstrained waveform is at only 56 percent (i.e., $\frac{1}{2}$) of the amplifiers peak linear power. This results in an inefficient use of the output amplifier.

Also, the biasing of the transmitter output amplifier so that the spectrally constrained waveform is at or near the top of the amplifier's linear region requires that the output amplifier be of significantly higher power than that required for the transmission of a spectrally unconstrained waveform. Such a higher-power amplifier is inherently more costly than its lower-power counterparts.

SUMMARY OF THE INVENTION

It is an advantage of the present invention that a circuitry and a methodology are provided that allow a transmitter output amplifier to be biased so that the spectrally unconstrained waveform is at or near the top of the amplifier's linear region without incurring clipping of a spectrally constrained waveform.

It is another advantage of the present invention that a circuitry and methodology are provided that allow a spectrally constrained waveform to have approximately the same magnitude as the spectrally unconstrained waveform without effecting a significant increase in spectral regrowth.

It is another advantage of the present invention that a circuitry and methodology are provided which allow a spectrally constrained waveform to be utilized with a continuous transmission scheme.

It is another advantage of the present invention that a circuitry and methodology are provided which allow efficient use of a transmitter output amplifier, thus allowing higher power output for a given output amplifier and a given bandwidth constraint than was previously feasible.

It is another advantage of the present invention that a circuitry and methodology are provided which allow efficient use of a transmitter output amplifier, which allows allowing a lower-power amplifier to be used for achieving given bandwidth constraints than was previously feasible, thus effecting a significant saving in the cost thereof.

These and other advantages are realized in one form by a constrained-envelope digital communications transmitter circuit. The transmitter circuit has a pulse-spreading filter configured to receive a quadrature phase-point signal stream of digitized quadrature phase points and produce a filtered signal stream, which filtered signal stream exhibits energy corresponding to each phase point spread throughout a plurality of baud intervals. The transmitter circuit also has a constrained-envelope generator coupled to the pulse-spreading filter and configured to produce a constrained-

bandwidth error signal stream. The transmitter circuit also has a combining circuit coupled to the pulse-spreading filter and to the constrained-envelope generator, which combining circuit is configured to combine the filtered signal stream and the constrained-bandwidth error signal stream to produce a constrained-envelope signal stream. The transmitter circuit also has a substantially linear amplifier with an input coupled to the combining circuit.

These and other advantages are realized in another form by a method for the transmission of a constrained-envelope communications signal in a digital communications system. The transmission method includes the step of filtering a quadrature phase-point signal stream to produce a filtered signal stream, which filtering step spreads energy from each phase point over a plurality of baud intervals. The transmission method also includes the step of generating a constrained-bandwidth error signal stream from the filtered signal stream and a threshold signal. The transmission method also includes the step of combining the filtered signal stream and the constrained-bandwidth error signal stream to produce a constrained-envelope signal stream. The transmission method also includes the step of linearly amplifying the constrained-envelope signal stream to produce the constrained-envelope communications signal. The transmission method also includes the step of transmitting the constrained-envelope communications signal.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete understanding of the present invention may be derived by referring to the detailed description and claims when considered in connection with the Figures, wherein like reference numbers refer to similar items throughout the Figures, and:

FIG. 1 depicts a simplified block diagram of a digital communications system in accordance with a preferred embodiment of the present invention;

FIG. 2 depicts a block diagram of a constrained-envelope digital communications transmitter circuit in accordance with a preferred embodiment of the present invention;

FIG. 3 depicts a 16-P-APSK constellation illustrating a locus of a quadrature phase-point signal stream over twelve exemplary consecutively mapped phase points in accordance with a preferred embodiment of the present invention;

FIG. 4 depicts a plurality of signal streams in accordance with a preferred embodiment of the present invention;

FIG. 5 depicts the phase-point constellation of FIG. 3 illustrating an exemplary locus of a filtered signal stream over the twelve consecutively mapped phase points of FIG. 3 in accordance with a preferred embodiment of the present invention;

FIG. 6 depicts a pair of Nyquist-type data bursts in accordance with a preferred embodiment of the present invention; and

FIG. 7 depicts a noise-influenced constellation illustrating constrained-envelope phase-point probabilities of the phase points of the constellation of FIG. 3 in accordance with a preferred embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 depicts a simplified block diagram of a digital communications system 20 and FIG. 2 depicts a block diagram of a constrained-envelope digital communications transmitter circuit 22 in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 1 and 2.

Digital communications system 20, as depicted in FIG. 1, includes a transmitter circuit 22 and a transmitter antenna 24 together configured to modulate and transmit a radio-frequency (RF) broadcast signal 26 to a receiver antenna 28 and a receiver circuit 30, together configured to receive and demodulate RF broadcast signal 26. Those skilled in the art will appreciate that the embodiment of system 20 depicted is a simplistic one for purposes of discussion only. In normal use, system 20 would likely be a complex system consisting of many more components and broadcast signals. It will be appreciated that the use of such a complex communications system for system 20 in no way departs from the spirit of the present invention or the scope of the appended claims.

Transmitter circuit 22 has a binary data source 32 providing a binary input signal stream 34. Binary data source 32 may be any circuitry, device, or combination thereof producing input signal stream 34. Input signal stream 34 is made up of binary data that may be pre-encoded in any desired manner. That is, input signal stream 34 may be made up of data that has no encoding, concatenated encoding, Reed-Solomon block encoding, or any other form of encoding desired for or required of the communications scheme in use.

In the preferred embodiment, input signal stream 34 is a stream of continuous data (as contrasted with burst data) passing to an input of a convolutional encoder 36. Convolutional encoder 36 convolutionally encodes (e.g., Viterbi encodes) input signal stream 34 into an encoded signal stream 38. The use of convolutional encoder 36 in transmitter circuit 22 and a like convolutional decoder (not shown) in receiver circuit 30 significantly reduces the error rate of the overall signal in a manner well understood by those skilled in the art. However, convolutional encoder 36 may be omitted.

Interleaver 40 temporally decorrelates encoded signal stream 38 to produce an interleaved signal stream 42. That is, the symbols making up the binary signal stream are temporally decorrelated (i.e., separated) in transmitter circuit 22 and temporally correlated in receiver circuit 30. This is done so that correlated errors produced by downstream transmitter components, discussed hereinbelow, will then be decorrelated through a complimentary de-interleaver located in receiver circuit 30 before convolutional decoding in receiver circuit 30.

In the preferred embodiment, interleaved signal stream 42 passes to an input of a phase mapper 44. Those skilled in the art will appreciate that interleaver 40 is not desired in all embodiments of transmitter circuit 22, for example when convolutional encoder 36 is omitted. When interleaver 40 is omitted, encoded signal stream 38 is passed directly to the input of phase mapper 44. When both convolutional encoder 36 and interleaver 40 are omitted, binary input signal stream passes directly to the input of phase mapper 44.

FIG. 3 depicts a sixteen phase-point polar amplitude and phase shift keying (16-P-APSK) constellation 46 illustrating a locus 48 of a quadrature phase-point signal stream 50 (FIG. 2) over twelve exemplary sequential phase points 52 in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 2 through 3.

Phase mapper 44 maps symbols (i.e., binary data units) present in interleaved signal stream 42, encoded signal stream 38, or input signal stream 34, into phase points 54 in phase-point constellation 46. While constellation 46 is depicted in FIG. 3 as a 16-P-APSK constellation, those skilled in the art will appreciate that the circuitry and

methodology of the present invention may be applied to all forms of constellations. The present invention is especially beneficial when used with constellations having rings of different magnitudes, i.e., amplitude and phase-shift keying (APSK) constellations. This is true because APSK constellations, requiring amplitude modulation of the signal, desirably use linear amplifiers to reproduce that amplitude modulation.

Each phase point 54 in constellation 46 represents a plurality, in this example four, of symbols. The values of the symbols in a given phase point 54 determine the location of that phase point 54 within constellation 46 in a manner well known to those skilled in the art.

Each quadrature phase point 54 may be thought of as having a vector value expressed as I,Q in the Cartesian coordinate system, where I is the in-phase (abscissa) value and Q is the quadrature (ordinate) value of the vector, or expressed as M,ϕ in the polar coordinate system, where M is the magnitude and ϕ is the phase angle of the vector. In this discussion, the M,ϕ designation will be used throughout, as the vector magnitude is the most discussed vector component.

In the exemplary 16-P-APSK constellation 46 of FIG. 3, each phase point 54 resides upon an outer ring 56 or an inner ring 58. Phase-points 54 residing upon outer ring 56 are outer-ring or maximum-magnitude phase points 60. That is, outer-ring phase points 60 have a maximum magnitude (maximum value of M) as represented by the radius of outer ring 56. For purposes of discussion, the magnitudes of outer-ring phase points 60 are normalized to 1.00.

Inner-ring phase points 62, i.e., those phase points 54 residing upon inner ring 58, have a lesser magnitude as represented by the radius of inner ring 58. For the exemplary 16-P-APSK constellation 46 depicted in FIG. 3, the magnitudes of inner-ring phase points 62 may desirably be approximately 0.63 when outer-ring phase point 60 magnitudes are normalized to 1.00.

FIG. 4 depicts a plurality of signal streams, in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 2 through 4.

The output of phase mapper 44 is phase-point signal stream 50. Phase mapper 44 processes one phase point 54 per unit baud interval 64. That is, phase-point signal stream 50 consists of a series of consecutive phase-point pulses 66, each of which represents one phase point 54, whose leading edges are one unit baud interval 64 apart. Those skilled in the art will appreciate that other embodiments of phase-point signal stream 50 are equally valid, that the embodiment utilized is dependent upon the circuitry producing and processing phase-point signal stream 50, and that the use of other embodiments of this or any other signal stream does not depart from the spirit of the present invention nor the scope of the appended claims.

FIGS. 3 and 4 illustrate a series of twelve exemplary sequential phase points 52, representative of a random data stream processed by transmitter circuit 22 (FIG. 2). These twelve exemplary phase points 52 reside at temporally consecutive locations labeled $t_0, t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9, t_{10}$, and t_{11} . These labels represent sequential integral times at unit baud intervals 64, i.e., integral-baud times, and indicate the leading-edge times of phase-point pulses 66. For purposes of simplification within this discussion, any occurrence at time t_n shall be referred to as "occurrence t^n ". For example, an exemplary phase point 52 occurring at time t_2 shall be referred to as phase point t_2 , and the associated phase-point pulse 66 whose leading edge occurs at time t_2

shall be referred to as phase-point-signal pulse t_2 . In other words, at time t_2 , phase point t_2 is clocked and phase-point-signal pulse t_2 begins. One unit baud interval 64 later, at time t_3 , phase point t_3 is clocked and phase-point pulse t_3 begins. This process continues indefinitely, with twelve exemplary phase points t_0 through t_{11} depicted in FIG. 3 and twelve corresponding phase-point-signal pulses t_0 through t_{11} depicted in phase-point signal stream 50 of FIG. 4.

Table 1 below illustrates the magnitudes for phase-point-signal pulses to through t_{11} .

TABLE 1

Phase-Point Pulse Magnitudes	
Phase-Point-Signal Pulse	Magnitude
t_0	Outer-Ring 68
t_1	Inner-Ring 70
t_2	Outer-Ring 68
t_3	Outer-Ring 68
t_4	Inner-Ring 70
t_5	Outer-Ring 68
t_6	Outer-Ring 68
t_7	Outer-Ring 68
t_8	Outer-Ring 68
t_9	Inner-Ring 70
t_{10}	Outer-Ring 68
t_{11}	Inner-Ring 70

Phase point t_0 is an outer-ring phase point 60. Phase-point-signal pulse to therefore has an outer-ring magnitude 68. In like manner, phase point t_1 is an inner-ring phase point 62 and phase-point-signal pulse t_1 has an inner-ring magnitude 70.

Phase-point signal stream 50 effects locus 48 through constellation 46. Locus 48 coincides with the location of each exemplary phase point t_0 through t_{11} in turn at unit baud intervals 64. In FIG. 3, locus 48 is depicted as effecting a minimum distance (straight line) path between adjacent exemplary phase points 52. Those skilled in the art will appreciate that locus 48 is so depicted solely for the sake of simplicity, and that in actual practice, locus 48 instantly jumps or snaps between exemplary phase points 52 in a discontinuous manner.

FIG. 5 depicts an expanded phase-point constellation 46' illustrating a locus 72 of a filtered signal stream 74 (FIG. 2) over twelve exemplary sequential phase points 52 in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 2 through 5.

In the preferred embodiment, phase-point signal stream 50 passes to the input of a pulse-spreading filter 76, preferably realized as a Nyquist-type filter, such as a Nyquist, root-Nyquist, raised cosine-rolloff, etc., filter. Pulse-spreading filter 76 filters phase-point signal stream 50 into filtered signal stream 74, depicted in FIG. 5. In orthogonal frequency division multiplex (OFDM) systems, also known as multitone modulation (MTM) systems, pulse-spreading filter 76 may be implemented using a transmultiplexer or equivalent circuitry.

In accordance with Shannon's theory, well known to those skilled in the art, pulse-spreading filter 76 produces at least two (only two in the preferred embodiment) output filtered-signal pulses 78, i.e., complex samples of filtered signal stream 74, for each input phase-point pulse 66 received. This is demonstrated in FIG. 4 where filtered signal stream 74 possesses two filtered-signal pulses 78 per unit baud interval 64. In the preferred embodiment, filtered-signal pulses 78

consist of alternating on-time pulses 80, i.e., samples of filtered signal stream at integral unit baud intervals 64, and off-time pulses 82, i.e., samples of filtered signal stream 74 between integral unit baud intervals. In effect, filtered signal stream 74 is made up of two interleaved data streams, an on-time signal stream 84 and an off-time signal stream 86.

On-time signal stream 84 is substantially a version of phase-point signal stream 50, wherein each phase-point pulse 66 has been reduced in duration from one unit baud interval 64 to a half-unit baud interval 88 to become on-time pulse 80 while maintaining substantially the same relative leading-edge time. That is, filtered-signal pulse to has substantially the same magnitude and substantially the same leading edge time as phase-point pulse to with approximately one-half the duration. Of course, those skilled in the art will appreciate that signal streams 74 and 84 may be delayed from signal stream 50 by a delay imposed by filter 76.

The generation of both on-time pulses 80 and off-time pulses 82 by pulse-spreading filter 76 effectively populates expanded constellation 46' (FIG. 5) with on-time phase-points 90 (circles) and off-time phase points 92 (squares). The original phase points 54 of constellation 46 (FIG. 3), i.e., the phase points carrying the intelligence to be communicated by transmitter circuit 22, are on-time phase points 90 of expanded constellation 46'.

Added to expanded constellation 46' are off-time phase points 92, with each off-time phase-point 92 occurring approximately midway in time between consecutive on-time phase points 90. Therefore, exemplary sequential phase points 52 become exemplary filtered phase points 94. Exemplary filtered phase points 94 are made up of alternating exemplary on-time filtered phase points 96 and exemplary off-time filtered phase points 98, and reside at temporally consecutive locations labeled $t_0, t_{0.5}, t_1, t_{1.5}, t_2, t_{2.5}, t_3, t_{3.5}, t_4, t_{4.5}, t_5, t_{5.5}, t_6, t_{6.5}, t_7, t_{7.5}, t_8, t_{8.5}, t_9, t_{9.5}, t_{10}, t_{10.5},$ and t_{11} . In FIG. 5, exemplary on-time filtered phase points 96 are located at integral-baud times ($t_0, t_1, t_2,$ etc.), whereas exemplary off-time filtered phase points 98 are located at fractional-baud (non-integral-baud) times ($t_{0.5}, t_{1.5}, t_{2.5},$ etc.).

The generation of off-time phase points 92 approximately midway in time between consecutive on-time phase points 90 causes filtered signal locus 72 to effect excursions having local peak magnitudes 99 greater than outer-ring magnitude 68. Such excursions occur because the immediate position of locus 72 at any given instant in time is not only a result of those phase points 54 proximate that position, but of a plurality of phase points 54 both preceding and following that instant in time. That is, in the preferred embodiment, the determination of the position of locus 72 at time $t_{2.5}$ (i.e., coincident with off-time phase point $t_{2.5}$) is determined not only by the positions of phase points t_2 and t_3 , but by the positions of numerous phase points 54 preceding phase point $t_{2.5}$ (i.e., phase points $t_2, t_{1.5}, t_1, t_{0.5},$ etc.) and the positions of numerous phase points 54 following phase point $t_{2.5}$ (i.e., phase points $t_3, t_{3.5}, t_4, t_{4.5},$ etc.).

This phenomenon is illustrated in FIG. 6, which depicts a pair of Nyquist-type datum bursts 100 in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. 2, 4, 5, and 6.

In the preferred embodiment, pulse-spreading filter 76 is realized as a Nyquist-type filter. Therefore, when a single phase-point pulse 66 is filtered by pulse-spreading filter 76, that single pulse 66 is transformed into a Nyquist-type datum burst 100 extending over a plurality of unit baud intervals 64. It is a property of Nyquist-type filters that

datum burst 100 attains a datum-burst peak value 102 (i.e., a local peak magnitude) at the primary sampling time of the specific phase-point pulse 66 (i.e., at time t_2 for phase-point pulse t_2), and attains a zero datum-burst value 104 (i.e., is equal to zero) at integral unit baud intervals 64 preceding and following peak datum-burst value 102 (i.e., at times $\dots, t_{-1}, t_0, t_1,$ and t_3, t_4, t_5, \dots , for phase point pulse t_2). In this manner, the energy of each pulse 78 is spread over a plurality of baud intervals 64 preceding and following the clocking instant (time t_2).

FIG. 6 illustrates Nyquist-type datum bursts 100 for phase-point pulses t_2 and t_3 , with datum burst t_2 depicted as a solid line and datum burst t_3 depicted as a dashed line. As an example, it may be seen from FIG. 6 that at time t_2 the value of datum burst 12 is peak datum-burst value 102. At every other time separated from time t_2 by an integral number of unit baud intervals 64, the value of datum burst t_2 is zero. An analogous condition occurs for datum burst t_3 .

The value of locus 72 is, at each moment in time, the sum of all datum bursts 100 at that moment. In the simplified two-datum-burst example of FIG. 6, locus 72, depicted by a dotted line, is the sum of datum burst t_2 and datum burst t_3 . Since datum bursts t_2 and t_3 are zero at each integral time t_n except times t_2 and t_3 , the value of locus 72 is also zero except at times t_2 and t_3 , where it assumes the peak values of datum bursts t_2 and t_3 , respectively.

The value of locus 72 at any instant in time between integral-baud times is the sum of the values of all datum bursts 100 at that instant. For example, in FIG. 6 where only two datum bursts 100 are considered, locus 72 has a value at time $t_{2.5}$ that is the sum of the values of datum bursts t_2 and t_3 at time $t_{2.5}$. Since datum bursts t_2 and t_3 both have significant positive values at time $t_{2.5}$, locus 72 has a value significantly greater than the maximum values of either datum burst t_2 or datum burst t_3 .

Since locus 72 describes the sum of all datum bursts 100, locus 72 is a function of the shape of the curves (FIG. 6) describing those datum bursts 100. That is, locus 72 is a function of a filtered-signal peak magnitude component of a filtered-signal complex digital value at any given point. The shape of the datum-burst curve is a function of the excess bandwidth factor, α , a design property of pulse-spreading filter 76. The smaller the value of α , the more locus 72 may rise above the peak datum burst values 102 of adjacent datum bursts 100. Typical designs of pulse-spreading filters 76 use α values of 0.15 to 0.5. For like-valued adjacent phase points 54 and an α value of 0.2, a maximum excursion magnitude 105 (i.e., the potential local peak magnitude 99 of locus 72) is approximately 1.8 times the value of the maximum phase-point magnitude. That is, the magnitude of the constrained envelope is approximately 1.8 times that of the unconstrained envelope. In the preferred embodiment depicted in FIGS. 3, 4, and 6, on-time phase points t_2 and t_3 are both outer-ring phase points 60 having a normalized outer-ring magnitude 68 of 1.00. Therefore, off-time phase point $t_{2.5}$ may have a normalized maximum excursion magnitude 105 of 1.8. This implies that transmitter circuit 22, to faithfully transmit phase point $t_{2.5}$ without excessive distortion, and without the benefit of the present invention, would require an output power of 3.24 (1.8^2) times the power required to transmit phase point t_2 or t_3 , which are representative of the highest magnitude intelligence-carrying phase points 54. This represents an inefficient use of available power.

The following discussion refers to FIGS. 2, 4, and 5.

Off-time signal stream 86, a portion of filtered signal stream 74, passes from an output of pulse-spreading filter 76

to an input of an off-time constrained-envelope generator 106. It is the task of off-time constrained-envelope generator 106 to produce an off-time constrained-bandwidth error signal stream 108 from off-time signal stream 86. A complex summing or combining circuit 110 combines off-time constrained-bandwidth error signal stream 108 with a delayed version of filtered signal stream 74 (discussed below) to produce a constrained-envelope signal stream 112. Constrained-envelope signal stream 112 is effectively filtered signal stream 74 with compensation for excursions of locus 72 with magnitudes greater than outer-ring magnitude 68.

A quadrature threshold generator 118 generates a quadrature threshold signal 120. In the preferred embodiment, threshold signal 120 is a steady-state, constant signal having a value approximately equal to outer-ring magnitude 68. Threshold signal 120 is used to establish a reference with which off-time signal stream 86 is compared. Those skilled in the art will appreciate that threshold signal 120 may assume many forms and values in keeping with the methodology and circuitry incorporated in the comparison. The use of other forms and/or other values does not depart from the spirit of the present invention nor from the scope of the appended claims.

Threshold signal 120 and off-time signal stream 86 are combined in an off-time complex summing or combining circuit 122 to produce an off-time difference signal stream 124. Off-time difference signal stream 124 is made up of a series of off-time difference pulses 126 whose values are the difference between the values of equivalent off-time pulses 82 and the value of threshold signal 120. Since any given off-time pulse 82 may have a value greater than, equal to, or less than the value of threshold signal 120, off-time difference signal stream 124 would normally be made up of a combination of off-time difference pulses 126 having positive, zero, and negative values.

Off-time difference signal stream 124 is passed to the input of an off-time discriminator 128 to produce an off-time error signal stream 130. In the preferred embodiment, off-time error signal stream 130 is a variation of off-time difference signal stream 124 in which all off-time difference pulses 126 having positive values are passed unchanged as off-time error pulses 132 while all other off-time difference pulses 126 are passed as zero-value pulses (i.e., eliminated). In other words, off-time error signal stream 130 is formed from pulses, the timing of which coincide with excursions of locus 72 beyond outer-ring magnitude 68 and the magnitudes of which correspond to the degree to which locus 72 passes beyond outer-ring magnitude 68.

Off-time error signal stream 130 is then passed to the input of an off-time pulse-spreading filter 134. Off-time pulse-spreading filter 134 is substantially identical to first pulse-spreading filter 76. That is, in the preferred embodiment, both pulse spreading filters 76 and 134 are realized as Nyquist-type filters with substantially identical transfer characteristics. Off-time pulse-spreading filter 134 produces off-time constrained-bandwidth error signal stream 108 and completes the action of off-time constrained-envelope generator 106.

Within off-time constrained-envelope generator 106, off-time pulse-spreading filter 134 receives one off-time error pulse 132 from off-time discriminator 128 per unit baud interval 64. Off-time pulse-spreading filter 134 then transforms each off-time error pulse 132 into a Nyquist-type error burst (not shown) extending over a plurality of unit baud intervals. Since off-time pulse-spreading filter 134 is a

Nyquist-type filter, each error burst attains an error-burst peak value (not shown) at the primary sampling time of the specific off-time error pulse 132 (i.e., at time $t_{2.5}$ for error pulse $t_{2.5}$), and attains a zero error-burst value (not shown) at integral unit baud intervals 64 preceding and following the peak error-burst value (i.e., at times $\dots, t_{1.5}, t_{0.5}, t_{1.5}$, and $t_{3.5}, t_{4.5}, t_{5.5}, \dots$, for error pulse $t_{2.5}$). In this manner, the energy of each off-time constrained-envelope error pulse 136 is spread over a plurality of baud intervals 64 preceding and following the clocking instant (time $t_{2.5}$). This results in the conversion of off-time error signal stream 130 into off-time constrained-bandwidth error signal stream 108. Off-time constrained-bandwidth error signal stream 108 is made up of off-time constrained-envelope error pulses 136. This operation is essentially the same as the operation of pulse-spreading filter 76 in the conversion of phase-point signal stream 50 into filtered signal stream 74 described hereinabove.

Since off-time constrained-envelope error pulses 136 are derived from off-time pulses 82, the error-burst peak and zero values occur approximately midway between integral baud times, i.e., at baud times $t_{0.5}, t_{1.5}, t_{2.5}$, etc., hence between datum-burst peak and zero values 102 and 104 of filtered signal stream 74.

The production of off-time constrained-bandwidth error signal stream 108 completes the operation of off-time constrained envelope generator 106.

Filtered signal stream 74 is also passed to the input of a delay element 138. Delay element 138 produces delayed signal stream 140, which is effectively filtered signal stream 74 delayed sufficiently to compensate for the propagation and other delays encountered in off-time constrained-envelope generator 106, and particularly in off-time pulse-spreading filter 134. In other words, delayed signal stream 140 is filtered signal stream 74 brought into synchronization with off-time constrained-bandwidth error signal stream 108.

Combining circuit 110 combines filtered signal stream 74, in the form of delayed signal stream 140, and off-time constrained-bandwidth error signal stream 108 to reduce peak magnitude components of filtered signal stream 74. A resultant constrained-envelope signal stream 112 is made up of a series of digital pulses 142 whose values are the difference between the values of corresponding filtered-signal pulses 78 and off-time constrained-envelope error pulses 136. The result is a series of digital pulses 142 whose values do not appreciably exceed outer-ring magnitude 68 of expanded constellation 46'.

In some embodiments of the present invention, certain of outer-ring phase points 60 may have magnitudes greater than outer-ring magnitude 68, i.e., may be located beyond outer ring 56. This condition may occur as a result of pulse-spreading filter 76 executing certain Nyquist-type functions well known to those skilled in the art. In such an embodiment, transmitter circuit 22 contains an on-time constrained envelope generator 106' in addition to off-time constrained-envelope generator 106 discussed above.

On-time signal stream 84, also a portion of filtered signal stream 74, passes from an output of pulse-spreading filter 76 to an input of on-time constrained-envelope generator 106'. It is the task of on-time constrained-envelope generator 106' to produce an on-time constrained-bandwidth error signal stream 108' from on-time signal stream 84. Combining circuit 110 combines both off-time and on-time constrained-bandwidth error signal streams 108 and 108' with the delayed version of filtered signal stream 74 (discussed below) to produce constrained-envelope signal stream 112.